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# METHOD FOR CHARACTERISING AN OPTICAL FIBRE LINK

## Field of the invention

[0001] The present invention is related to a method for characterising an optical fibre link by analysis of a Rayleigh backscatter signal, from which the spatial distribution of the beat length, the coupling length and the PMD (Polarization Mode Dispersion) along the link can be determined.

## State of the art

[0002] The use of dispersion-shifted and dispersion compensating fibres has minimised the effect of chromatic dispersion on the bandwidth of an optical link. Polarisation mode dispersion (PMD) has therefore become the most serious limiting factor in high-speed optical communication systems. There exist several measurement techniques of PMD, but they only allow for measuring the global value and do not give information about the distribution of PMD along the fibre length. Measuring the spatial distribution of PMD is, however, important. Such a measurement would indeed allow to locate the bad trunks in an optical link, causing high PMD value. This can be essential in the frame of a network maintenance and upgrade.

[0003] The PMD of a fibre depends on two parameters: the beat length ($L_B$) and the coupling length ($L_C$). The beat

length depends on the birefringence of the fibre and the coupl _g length is related to the phenomenon of polarisation mode coupling. Measuring the spatial distribution of PMD therefore consists of measuring the distribution of both the beat and coupling lengths.

[0004] Most of the techniques proposed for measurement of the distributed PMD are based on polarisation-optical time domain reflectometry (POTDR). The concept of POTDR was introduced by A. Rogers in the 80's (see *A. Rogers, 'Polarization-optical time domain reflectometry: a technique for the measurement of field distributions'*, Applied Optics, vol. 20, pp. 1060-1074, 1981). It basically consists of measuring the polarisation properties of the Rayleigh backscatter signal when an optical pulse propagates down the fibre. Some POTDR-based techniques have since been developed for PMD characterisation. Most of them allow a measurement of the beat length distribution along an optical link and, therefore, do not allow the complete determination of the PMD. However, Sunnerud presented a POTDR-based set-up enabling the measurement of the accumulation of PMD along the fibre (see *H. Sunnerud et al., 'Polarization-Mode Dispersion measurements along installed optical fibers using gated backscattered light and a polarimeter', J. of Lightwave Technol., vol. 18, pp. 897-904, 2000*). This method requires POTDR measurements at several wavelengths. A technique based on the measurement of the degree of polarisation by using a POTDR set-up has also been presented in *'Distributed detection of high-PMD sections on installed fibers using a polarization-OTDR', M. Leblanc, Proc. OFMC'01, pp. 155-162, 2001*, and is related to the patent application US 2003/0174312. This technique does not allow quantification of the PMD, but enables to obtain distributed information about the level of PMD. Moreover

this technique requires the complete measurement of the state of polarisation of the backscattered signal. More recently, Galtarossa described another technique for the PMD measurement for which the coupling length is determined from the correlation of the birefringence vector (see '*Measurement of birefringence correlation length in long, single-mode fibers', Galtarossa et al., Opt. Lett., vol. 26, pp. 962-964, 2001*), which also requires the measurement of the polarisation states of the backscattered signal. Moreover, this technique requires a quite small duration of the pulses launched in the optical fibre: 5-10 ns.

[0005] In '*Polarization mode dispersion mapping in optical fibers with a Polarization-OTDR', M. Wuilpart, G. Ravet, P. Mégret and M. Blondel, Photon. Technol. Lett., vol. 14, pp. 1716-1718, 2002*, the authors describe an analysis of the POTDR signal which allows a mapping of the PMD along an optical fibre link by quantifying the PMD on each fibre of the link. The main advantage of that technique is that it does not require the complete measurement of the backscattered polarisation state evolution and only uses a linear polariser at the fibre input, which is quite simple to implement. The determination of the beat length, the coupling length and finally the PMD is based on the analysis of the statistical properties of the extrema present in a POTDR trace.

[0006] In said paper by Wuilpart et al. the spatial distribution of the linear birefringence $\delta$ is characterised by a Rayleigh statistical distribution along the fibre length and it is assumed that the rate of change of the birefringence angle q is described by a Gaussian distribution with zero mean and standard deviation $\sigma$ depending on the polarisation mode coupling strength. The circular birefringence is neglected. The corresponding

measurement set-up is shown in Fig.1. The OTDR pulses (10 ns) externally modulate a 1553 nm DFB laser via a pulse generator and an electro-optic modulator (EOM). After amplification, the pulses are launched into the fibre through an acousto-optic modulator (AOM), which suppresses the amplified spontaneous emission noise of the erbium doped fibre amplifier between two successive pulses. A linear polariser is placed at the fibre input and a polarisation controller (CP) is used to obtain the maximum power after the polariser.

[0007] Fig. 2 shows three simulated POTDR traces corresponding to the POTDR arrangement and obtained for different values of the beat length and an identical $\sigma$ value. One can easily observe that the number of maxima strongly depends on $L_B$.

[0008] The calculation of the beat length is based on the measurement of the number of maxima of the POTDR trace. Fig.3, which has been obtained by simulation, presents the number n of maxima per unit of length in function of the beat length for different values of $\sigma$. This figure shows that n varies not only with $L_B$ but also with the strength of the polarisation mode coupling ($\sigma$). In order to estimate $L_B$ from n, the curve corresponding to $\sigma$ = 10 (the dashed curve in Fig.3) is used. This choice indeed minimises the maximum possible error if one assumes that $\sigma$ is smaller than 15 degrees/m. Consequently, this method allows only to give an approximate value of the beat length $L_B$. A relationship between the coupling length $L_C$ and $\sigma$ can be derived and one can obtain:

$$L_C = \frac{0.879}{\sigma^2}$$

[0009] A statistical approach is then used for determining the coupling length from the POTDR trace. Fig.

4 shows different POTDR traces that were obtained by simulation for a beat length of 25 m and for different values of σ: 2, 4 and 8 degrees/m, respectively. One can observe that the lower envelope of the curves varies in a smoother way when σ decreases and therefore when $L_C$ increases. Defining $\Delta P_i$ as the absolute value of the difference in ordinate between two successive minima of the POTDR trace P one can write :

$$\Delta P_i = |P(z_i) - P(z_{i+1})|$$

where $z_i$ and $z_{i+1}$ correspond to the distances of the $i^{th}$ and the $i+1^{th}$ minimum, respectively.

[0010] A new parameter ξ can then be calculated as

$$\xi = < \Delta P_i >_i$$

where $<.>_i$ denotes the mean value for i varying from 1 to the number of minima of the POTDR trace. ξ is a measure of the speed variation of the lower envelope of the backscattered signal along the fibre length. Fig. 5 (obtained by simulation) shows the evolution of ξ according to σ for different values of the beat length $L_B$. The values are here expressed in dB because ξ has been calculated directly from the POTDR trace.

[0011] The procedure for the determination of $L_C$ is the following. From the POTDR trace, the number of maxima and each $\Delta P_i$ are measured. An approximate value of the beat length is then deduced by the method previously described and ξ is calculated by averaging $\Delta P_i$. Finally σ can be deduced from ξ by using the curve of Fig. 5 corresponding to the correct beat length and then $L_C$ is calculated by means of the relation $L_C=0.879/\sigma^2$ stated above. Because $L_B$ is an approximate value, the calculated coupling length $L_C$ will also be an approximation.

[0012] From the measurement of the beat length and the coupling length, it is easy to determine an approximate value of the PMD value by

$$PMD^2 = \frac{1}{2}\left(\frac{\lambda}{cL_B}\right)^2 L_C^2 \left(\frac{2L}{L_C} - 1 + e^{-\frac{2L}{L_C}}\right)$$

where c is the light velocity in a vacuum, λ the measurement wavelength and $L$ the fibre length. It should be emphasised that the final PMD value is approximate: this is due to the approximation done on the beat length measurement. This process can be repeated for each contribution in the POTDR signal corresponding to the different fibres of the optical link: it is therefore possible to map the PMD along this link.

[0013] The method as described above has some important drawbacks and limitations. It only yields approximate values of $L_B$, $L_C$ and the PMD. Further, the presented POTDR traces were assumed ideal. It supposes ideal characteristics of the various components of the experimental set-up. In practice, the set-up is characterised by some imperfections, which cause a distortion of the ideal POTDR signal. Therefore the method as such cannot be directly applied. The POTDR signal is also affected by noise: detector noise and residual coherence noise, which adds a series of minima and maxima to the POTDR trace. The final value of the measured PMD can therefore be erroneous.

## Aims of the invention

[0014] The present invention aims to provide a method for analysing a backscatter signal for determining in an accurate way the spatial distribution of the beat length, the coupling length and the polarisation mode dispersion.

Summary of the invention

[0015] The invention relates to a method for characterising an optical fibre link by its beat length, coupling length and polarisation mode dispersion distribution. It comprises the steps of

- sending a pulsed signal along the optical fibre link and measuring the backscattered signal (preferably a POTDR signal), after passing through a polariser,
- deriving the length of the optical fibre, the average power difference between two successive minima of the backscattered signal and the number of maxima per unit length,
- in an iterative way determining a beat length interval and an interval for the polarisation mode coupling parameter, until the length of the intervals is below a predetermined value, yielding a value for the beat length and the coupling length,
- calculating the polarisation mode dispersion.

[0016] Preferably the POTDR signal is an ideal POTDR signal.

[0017] Advantageously the POTDR signal is the convolution of an ideal POTDR signal and a signal depending on the pulse shape. In an alternative embodiment the POTDR signal further is convoluted with a signal taking into account the time jitter introduced by the measurement set-up.

[0018] In a specific embodiment a smoothing algorithm is applied to the POTDR signal.

[0019] In another object the invention relates to a method for characterising an optical link consisting of a concatenation of several fibres, wherein the method as previously described is applied to each fibre.

[0020] The invention also relates to the use of a method as described above to locate the position of polarisation mode dispersion sources within an optical fibre link.

[0021] In an advantageous embodiment the method as described is used in telecommunication networks. Alternatively, it can be applied in fibre sensing applications.

## Short description of the drawings

[0022] Fig. 1 represents the set-up for measuring a POTDR trace.

[0023] Fig. 2 represents three simulated POTDR traces for a given $\sigma$ and for different $L_B$ values.

[0024] Fig. 3 represents the number of maxima per unit length versus $L_B$ for different values of $\sigma$.

[0025] Fig. 4 represents simulated traces for a given beat length and different values of $\sigma$.

[0026] Fig. 5 represents the evolution of $\xi$ as a function of $\sigma$ for different values of $L_B$.

[0027] Fig. 6 represents the determination of the beat length interval.

[0028] Fig. 7 represents the determination of the interval for $\sigma$.

[0029] Fig. 8 represents the distorsion of the POTDR signal due to the imperfections of the set-up (pulse shape + time jitter).

[0030] Fig. 9 represents the evolution of n with the beat length when the imperfections of the set-up are taken into account.

[0031] Fig. 10 represents the evolution of $\xi$ with $\sigma$ when the imperfections of the set-up are taken into account.

[0032] Fig. 11 represents the simulated and measured probability density function of Δ.

[0033] Fig. 12 represents the window algorithm that can be used for calculated the local PMD.

## Detailed description of the invention

[0034] It is first shown how the polarisation mode dispersion from a POTDR signal can be determined in an accurate way ($L_B$ is not approximately determined anymore) by analysing the statistical properties of its extrema. Suppose first that σ falls within the range [0,15] degrees/m, which means that the coupling length is assumed to be larger than 12.8 m. This σ interval has been chosen such that it corresponds to the values measured on real fibres.

[0035] From a POTDR signal, the fibre length L, ξ and the number of maxima per unit of length, $n_m$, are easily measurable. After measuring $n_m$, it is possible to determine a first interval $\left[L^1_{B_{low}}, L^1_{B_{up}}\right]$ for the beat length of the fibre under test so that:

$$L_B \in \left[L^1_{B_{low}}, L^1_{B_{up}}\right]$$

$L^1_{B_{low}}$ and $L^1_{B_{up}}$ are determined by the intersections of the curves $n(L_B,\sigma)$ corresponding to σ = 0 and σ = 15 degrees/m with the straight line $n = n_m$ as shown on Fig. 6.

[0036] When the first beat length interval is determined, the curves $\xi(\sigma,L_B)$ can be used to define an interval $\left[\sigma^1_{low}, \sigma^1_{up}\right]$ for the σ value of the fibre under test so that :

$$\sigma \in \left[\sigma^1_{low}, \sigma^1_{up}\right]$$

$\sigma_{low}^{1}$ and $\sigma_{up}^{1}$ are determined by the intersections of the curves ξ(σ,$L_B$) for $L_B = L_{B_{low}}^{1}$ and $L_B = L_{B_{up}}^{1}$ with the straight line $\xi = \xi_m$, where $\xi_m$ is the ξ value of the fibre under test measured from the POTDR signal. This principle is illustrated in Fig. 7.

[0037] After the determination of $\sigma_{low}^{1}$ and $\sigma_{up}^{1}$, the curves n($L_B$,σ) for $\sigma = \sigma_{low}^{1}$ and $\sigma = \sigma_{up}^{1}$ can be calculated. A new beat length interval is then deduced as previously explained by Fig. 6, but using the curves obtained for $\sigma = \sigma_{low}^{1}$ and $\sigma = \sigma_{up}^{1}$ instead of σ = 0 and σ = 15 degrees/m.

[0038] This new beat length interval denoted $\left[L_{B_{low}}^{2}, L_{B_{up}}^{2}\right]$ is included in $\left[L_{B_{low}}^{1}, L_{B_{up}}^{1}\right]$ and gives a smaller range for the beat length of the fibre under test. Fig. 7 is then used again to calculate a new σ interval $\left[\sigma_{low}^{2}, \sigma_{up}^{2}\right]$ by using the curves ξ(σ,$L_B$) obtained for

$$L_B = L_{B_{low}}^{2} \text{ and } L_B = L_{B_{up}}^{2}$$

This new interval gives a smaller range for the σ value of the fibre under test. This process is repeated until small enough intervals are obtained for the beat length $L_B$ and for σ.

[0039] When the beat length $L_B$ and σ are determined, the PMD is finally calculated by means of the relationship:

$$PMD = \sqrt{\frac{8}{3\pi}}\sqrt{\frac{1.545}{\pi}\left(\frac{\lambda}{L_B\ \sigma^2\ c}\right)^2\left(\frac{\sigma^2 L}{0.439} - 1 + e^{-\frac{\sigma^2 L}{0.439}}\right)}$$

[0040] If the optical link to be characterised consists of a concatenation of several fibres, the method

is applied to each fibre of the link and their beat and coupling lengths are therefore determined independently of each other. In this way, the PMD mapping is possible along the link.

[0041] The method for analysing the backscatter signal as described offers several advantages :

- it requires only the access to one end of the optical fibre link to be characterised;
- it is based on a POTDR arrangement, but does not require the complete measurement of the complete state of polarisation of the backscattered signal. Only a simple polariser is required;
- it involves a POTDR measurement at only one wavelength;
- it gives accurate (not approximate) values for the beat length, the coupling length and the PMD.

[0042] In practice, the final measured signal is also affected by noise. This noise is due to the detector noise and to the presence of a residual coherence noise. As the determination of the PMD is based on the detection of extrema, it is obvious that this noise will affect the results.

[0043] As already mentioned before, the measured signal is also affected by the imperfections of the experimental set-up like the finite pulse shape and the time jitter of the electronic equipment.

These phenomena (noise and imperfections of the measurement set-up) lead to a distortion of the POTDR signal. Therefore it cannot be used directly to deduce the PMD map.

The width of the optical pulses launched into the fibre under test is finite and can be non-rectangular. Consequently, the backscattered power measured at the POTDR corresponds to an average of the ideal signal over a small spatial window depending on the pulse shape. The resulting

signal measured at the POTDR is in fact the convolution product between the ideal signal and the shape of the pulse:

$$P_{pulse}(z) = P(z) \otimes P_{shape}(z)$$

where $P_{pulse}(z)$ is the power measured by the POTDR according to a certain pulse shape. $P(z)$ is the ideal POTDR signal and $P_{shape}(z)$ is the power distribution along the pulse. Hence the Fourier transform of $P_{pulse}(z)$ becomes:

$$P_{pulse}(k) = P(k)P_{shape}(k)$$

where $P_{pulse}(k)$, $P(k)$ and $P_{shape}(k)$ are the Fourier transforms of $P_{pulse}(z)$, $P(z)$ and $P_{shape}(z)$, respectively.

[0044] Moreover the electronic equipment is not perfect: it is subject to a time jitter, i.e. the time delay between two successive pulses is not constant. This phenomenon strongly affects the averaging process of the POTDR. If we suppose that the number of pulses involved in the averaging process of the OTDR is large enough and that the time jitter is a random variable characterised by a Gaussian distribution of zero mean and standard deviation $\sigma_{tj}$, the signal detected at the POTDR can be written as:

$$P_m(z) = P_{pulse}(z) \otimes e^{-\frac{z^2}{2\sigma_{tj}}}$$

where $P_m(z)$ is the power measured by the POTDR taking into account the pulse shape and the time jitter. Hence the Fourier transform of $P_m(z)$ becomes:

$$P_m(k) = P_{pulse}(k)\sigma_{tj}e^{-\frac{k^2\sigma_{tj}^2}{2}}$$

The pulse shape and the time jitter have for effect to distort the measured backscattered signal. An example is shown on Fig. 8, which has been obtained for parameters of the experimental set-up. The signals (a) and (b) correspond

to the ideal and affected signals, respectively. One can clearly observe that the signal is strongly distorted.

[0045] Because of these imperfections, the method described above cannot be used directly: the curves $n(L_B,\sigma)$ and $\xi(\sigma,L_B)$ are indeed based on ideal POTDR signals obtained by simulations. Therefore the effects of the pulse shape and the time jitter should be included in the calculation of $n(L_B,\sigma)$ and $\xi(\sigma,L_B)$. In the case of the parameters of the experimental set-up and a pulse duration of 10 ns, these new curves are shown on Fig. 9 and 10. In order to deduce these curves, ideal POTDR traces have been simulated and the effects of the imperfections have been taken into account by using the above expressions for $P_{pulse}(z)$ and $P_m(z)$. Consequently, when the imperfections of the experimental set-up are taken into account, the PMD map of an optical link can still be determined. The same reasoning as the one explained previously has to be applied on the POTDR signal by using the new set of curves $n(L_B,\sigma)$ and $\xi(\sigma,L_B)$ described in fig. 9 and 10. As the pulse shape is now taken into account, it is possible to launch a larger pulse in the fibre (50 ns, for example), which will increase the system dynamics. The maximum measurable length will therefore be greater.

[0046] As already indicated, the final measured signal is also affected by noise. This noise is due to the detector noise and the presence of a residual coherence noise. Its main effect is to add a series of minima and maxima to the POTDR trace. The values of n and $\xi$ cannot thus be correctly measured and the final calculated PMD will be erroneous. In order to solve this problem, a smoothing algorithm is applied to the backscattered POTDR signal $P_m(z)$. This algorithm consists of generating the signal $P_s(z)$ such that:

$$P_s(z)=\frac{1}{L_s}\int_{z-\frac{L_s}{2}}^{z+\frac{L_s}{2}} P_m(z')\ dz'$$

$P_s(z)$ is therefore the mean value of $P_m(z)$ on a distance interval $L_s$ around z. The number of maxima and the distances $z_k$ corresponding to the locations of the minima of the POTDR trace are then calculated from the smoothed signal in order to ignore the influence of the small peaks generated by the noise. Afterwards, when the positions $z_k$ are known, $\xi$ is calculated from $P_m(z)$. When noise is present, the number of extrema of $P_s(z)$ depends of the smoothing parameter $L_s$. So, the main problem is to choose the correct smoothing parameter to be applied to the POTDR signal.

[0047] The location of the minima of the smoothed signal can be used to estimate the probability density function of $\Delta$, denoting the difference in z between two successive minima. This estimation can then be compared to the density probability function of $\Delta$ of a POTDR trace obtained by means of simulations taking into account the parameters $L_B$ and $\sigma$ calculated from the smoothed signal. If the probability density functions of $\Delta$ obtained from $P_s(z)$ and from the simulation do not match, it means that the noise contribution is significant. The smoothing parameter $L_s$ will therefore be chosen such that the corresponding probability density function obtained from measurements can be correctly fitted by the probability density function derived from simulations: $L_s$ is therefore chosen such that the noise contribution is reduced. Fig. 11 illustrates this concept. Figures (a), (b) and (c) show the probability density functions obtained by measurement (circles) and by simulation (crosses) for a given optical fibre and for an

$L_s$ value of 3, 4 and 5 m, respectively. One can clearly observe in this case $L_s$ = 3 m gives the best fitting.

[0048] The invention also provides a technique which will allow to locate more accurately the position of the PMD source within the fibre. The basic idea consists in applying the described method on a distance window (1 km, for example), which slides along the fibre length. By comparing the obtained PMD's on several successive windows as shown on Fig. 12, it is possible to locate more accurately high PMD sources within the optical fibre.

[0049] POTDR can also be used in fibre sensing. The polarisation properties indeed depend on several external effects like strain, temperature, electric and magnetic fields. Strain, twist, temperature, electric and magnetic fields affect the birefringence within the fibre and consequently, the mean beat length. The method of the invention, which measures the spatial distribution of the beat length, therefore allows to measure the spatial distribution of these external effects after calibrating the sensing fibre.